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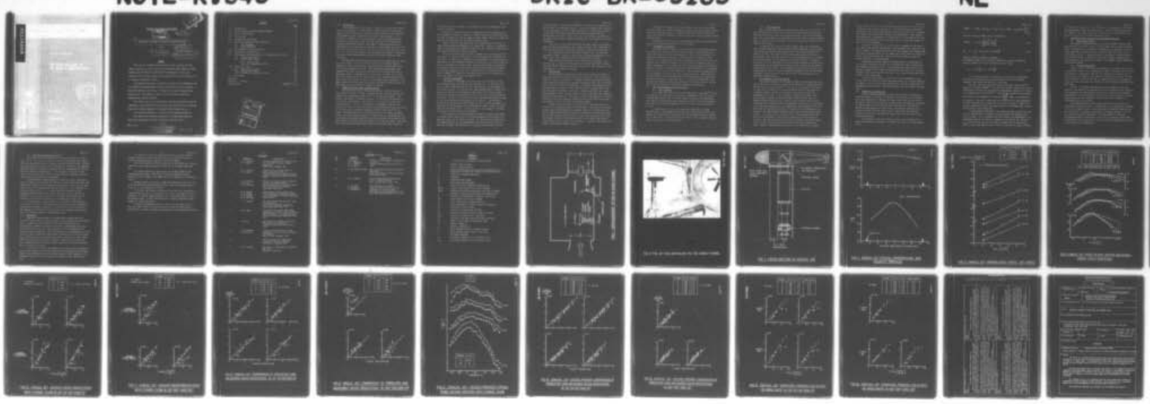

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The effect of flight on the noise of subsonic jets*

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SUMMARY

The noise of a single-stream circular jet and a coaxial jet with coplanar nozzles of 2.5 area ratio has been measured under simulated flight conditions in the RAE 24 ft wind-tunnel. The majority of tests were conducted with the single-stream jet and primary section of the coaxial jet at a nominal temperature of 880 K.

The data have been used to quantify the effect of jet temperature and were combined with measurements from an earlier test series to establish a prediction method for the effect of flight on the noise of single-stream subsonic jets. This method is based on jet noise theory modified by experimentally derived constants.

For coaxial jets it is concluded that the noise reductions, which are independent of the secondary stream velocity, are predicted to an acceptable degree by the method suggested for unheated single-stream jets.

The prediction methods are suitable for both OASPLs and spectra.

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CONTENTS

1.0 Introduction

The determination of the effect of flight on jet noise from aircraft fly-over measurements is complicated by a number of factors, such as the impurity of the noise source, engine installation effects, the properties of the atmosphere and the transient nature of the acoustic signal. It is possible to eliminate, or at least alleviate, most of these problems by carrying out tests using 'clean' jet rigs installed in wind-tunnels that have been acoustically treated. The method is especially attractive if measurements can be made with the microphone located within the tunnel flow. The 24 ft low speed wind-tunnel at the Royal Aircraft Establishment provides such a facility, and accordingly a test programme was planned to investigate the noise of both single-stream and coaxial jets under simulated flight conditions.

The programme, which covered only subsonic jet conditions, was carried out in two stages. The first phase[1,2] used jets of nominally ambient temperature, and concentrated on a single-stream jet although some coaxial jet noise measurements were taken. The single-stream measurements were compared with theory and the data from both types of nozzles were used to formulate tentative recommendations for the effect of flight on jet noise. The second stage extended the work to heated jets; single-stream jets were again studied and coaxial jet noise was investigated more extensively. This paper reports the second stage of the tests, and makes further proposals for the prediction of the effects of flight on jet noise.

2.0 Flight simulation using coflowing streams

Wind-tunnels and other coflowing streams are a recognised means of simulating the effects of flight on various aircraft noise sources and past studies have included small model jets[1,2,3] and complete engines[4]. The simplest experimental arrangement consists of a jet source surrounded by an airflow just wide enough for the potential core to sheath the main noise-producing region of the jet. Although this arrangement allows the jet dynamics and structure to develop correctly, the microphone must be positioned in the stationary surrounding atmosphere and hence corrections[3,5,6] are needed for propagation effects in the shear-layer of the flight simulation stream. The uncertainties caused by the shear-layer are eliminated when the microphone is positioned inside the flow and this method, established in the earlier phase of the work, has been followed in the present study. Since that time, there has been further work elsewhere which throws light on some of

the uncertain factors inherent in the technique when the microphone is positioned in the flow.

The first of these factors is the suggestion that the sensitivity of the microphone is affected. However, a limited study by Neise[7] has shown that any loss of sensitivity over the range of tunnel speeds used here is small and therefore no corrections for this effect have been made.

Again, there are some doubts about the contamination of the data by sound reflected from the boundary of the tunnel flow. However, a theoretical study of this problem by Jacques[5] has shown that the reflection coefficient is very small and this effect can be neglected.

As in the earlier series of tests, a Doppler shift has been applied to the spectra to correct for the absence of motion between the microphone and the nozzle. In addition, to take the noise measurements at constant angles of sound emission, the microphone positions were adjusted to allow for sound convection according to the tunnel speed. There has been further confirmation from Jacques' work that no other corrections are needed when the microphone is positioned inside the flow. All of these points are discussed in more detail elsewhere[1,2,5] where the corrections are given for the convection of sound with tunnel flow and for the Doppler shift.

3.0 The 24 ft wind-tunnel

The RAE 24 ft wind-tunnel was used for the earlier phase of tests, the principal change now being the use of heated jets. In the event, the rise in tunnel temperature was only 2°C, and there were no constraints on the tunnel operation. Previously, there were problems owing to slight reverberations of sound at low frequencies, high noise levels from the tunnel driving fan and vibration-induced noise due to the tunnel flow buffeting the microphone. In fact, it was decided that the reverberations were bad enough for all of the forward-arc measurements to be rejected. The problem of reverberation remained during these tests but since a recent assessment has shown that the noise changes in the mid-frequency region - where the reverberations are insignificant - are very similar to the changes in the OASPL, forward-arc data are included in this Report.

The noise from the tunnel driving fan remained a problem even though the highest levels, which occur at very low frequencies, were removed by a high-pass filter set to cut-off at 200 Hz. All the data were corrected for the background noise but some measurements were rejected because the fan noise was too high. The criterion for acceptance was the same as in the

first test series: only those measurements 6 dB above the background noise were retained for subsequent analysis. Because the maximum tunnel speed was 50 m/s, the highest useful jet speed was 450 m/s. Although greater values of both these velocities would have been desirable to make them more representative of typical flight cases, it is nevertheless considered that the range covered leads to prediction methods that are suitable for aircraft assessments.

The source of the vibration-induced noise was traced to the adaptor used with the 6 mm microphone. The problem was easily cured, therefore, by using a 12 mm microphone, which has no adaptor, during the second stage.

The wind-tunnel is fully described elsewhere[8], but the pertinent features are shown in Figure 1, which shows the general arrangement of the tunnel with a rig in position, and by the photograph in Figure 2.

When the fan is stationary but the model jets are blowing, a low velocity, V_{TO}, is induced in the tunnel, and although the effect is small, the value has been subtracted from the jet velocity. The correction is not necessary when the tunnel is running.

4.0 The jet rigs

The jet rigs used during this second stage of tests were similar to those used during the earlier tests with cold air jets. The principal new feature is shown in the Figure 2. A wooden fairing surrounding the vertical supply pipes was removed and the hydrogen burning air heater for the primary jet was installed in about mid-position. To attenuate any combustion noise, the pipe above the burner was lined internally with a ceramic fibre 25 mm deep faced with a perforated metal sheet. Additionally there was a lined plenum chamber at floor level to reduce the noise produced by the compressor and other internal sources. The by-pass stream for the coaxial jet tests was supplied by air from a separate compressor through the other vertical pipe positioned on top of a similarly lined plenum chamber.

Figure 2 shows the coaxial rig in position. The nozzle exits are coplanar, and the primary nozzle of 65 mm diameter, also used for the single-stream tests, was surrounded by a secondary nozzle of 2.5 times this area. For the single-stream tests the nozzle was attached to a cascade corner that had the same internal design as the one used in the coaxial jet rig. Thus, the internal features of the primary section of the coaxial rig and the single-stream rig were similar in all respects. A sketch of the coaxial rig without its fairing is shown in Figure 3.

The nozzles now being used are much smaller than those tested during the first stage; for example the diameter of the single-stream nozzle has been reduced from 102 mm to 65 mm. To augment these data so that the effect of nozzle size could be determined a few tests were also carried out with an 86 mm diameter nozzle.

Checks with wool tufts on the metal fairings around the nozzles showed that the flow remained attached at all tunnel speeds.

5.0 Aerodynamic calibrations

To enable the jet velocity to be calculated, the relationships between the nozzle exit conditions and the reference pressure and temperature were established before the noise tests commenced. Ideally, there should be flat temperature and pressure profiles at the nozzle exit for datum jet noise studies. But, although the survey showed acceptable velocity profiles for the unheated jet (a typical variation was ±1 m/s outside the boundary layer) the profile temperature for the heated jets had a pronounced peak, as indicated in Figure 4. However, the velocity profile also shown in Figure 4, is reasonably flat, and it is clear from the comparison of the predicted and measured noise levels presented in Figure 5 that those profiles have only a small effect on the noise despite the comparison being affected somewhat by the tunnel reverberations, especially in the forward-arc. In view of this agreement, all of the data were related to conditions estimated for the centre-line of the jet, and all jet velocities were calculated assuming isentropic flow.

6.0 The test programme and data acquisition

6.1 Test programme

It is known from studies of jet noise under static conditions[10,11] that the effect of jet temperature on jet noise is dependent on the jet velocity. To investigate whether this is so under flight conditions, the measurements were taken at a nominal peak total temperature of 880 K at three velocities; the actual conditions being 288 m/s at 893 K, 355 m/s at 878 K, and 446 m/s at 873 K.

For the coaxial jet tests the primary jet temperature was again nominally 880 K - the maximum variation from this temperature was 13°C. The primary jet velocities were the same as for the single-stream tests; 288 m/s, 355 m/s and 446 m/s. The by-pass flow was varied so that a range of velocity ratios from 0.6 to 1.0 could be studied.

6.2 Data acquisition

The noise was measured at constant emission angles of 35°, 45°, 60°, 75°, 90°, 105° and 120° to the jet axis by the 12 mm Bruel and Kjaer microphone, which was fitted with a nose cone, traversed linearly 2.07 m from the nozzle axis. The rig was offset 1.2 m from the axis of the tunnel to allow the microphone to remain inside the potential core of the tunnel flow for most of the range of the traverse.

To maximise the level of the useful signal, after the low frequency fan noise was removed by a General Radio type 1952 high-pass filter the microphone output was amplified and analysed into third-octave bandwidths from 250 Hz to 20 kHz. The majority of test points were analysed on-line by a General Radio 1926 real time analyser set to an integrating time of 4 seconds. The digitised output from the analyser was processed further by a computer which also corrected the spectra for the microphone frequency response, microphone directivity and atmospheric absorption before calculating the OASPL by summing the spectrum levels. The microphone was calibrated at regular intervals during the tests by a Bruel and Kjaer pistonphone as was the electronic equipment by tones injected at each third-octave centre frequency at the microphone cathode-follower.

7.0 An assessment of the data quality

The general agreement of the measured OASPLs with the predicted levels implied that only jet noise was being produced during the single-stream tests and that rig noise was unimportant. This was not an unexpected conclusion for there was no evidence of rig noise during the earlier tests and the use of smaller diameter nozzles in the present tests should increase the dominance of jet noise. It was, therefore, somewhat surprising to find that the spectra showed distortions at high frequencies that were not present during the earlier tests. Figure 6 shows typical results and the comparison with the predicted spectra highlights the distortions at both ends of the spectrum, especially for the measurements taken laterally to the jet. Whilst the low frequency distortion is believed due to reverberations, the anomaly at the high frequency remains a puzzle even after extensive investigations. It is quite clear that distortions of this magnitude would cast doubt on the usefulness of the spectra if absolute noise levels were of interest. But since this paper deals with the changes of noise with tunnel flow it is only necessary to determine whether these are substantially valid. Figure 7, which presents the effect of the tunnel flow on typical

spectra, shows that the noise reductions in the distorted region are similar to those at other parts of the spectra. This observation is particularly interesting, for if the distortions were caused by rig noise, it is unlikely that similar reductions would be noted at all frequencies. Thus, based on this evidence it is reasonable to conclude there is no evidence of rig noise and that the distortions have only a minor effect, if any, when changes in noise level are considered.

It has not been possible to mount a similar argument for the case of the coaxial jets, because the presence of the secondary flow complicates the issue. However, the primary section has the same design as the single-stream rig, and the characteristics of the changes in spectrum level are similar to those of the single-stream jet. Hence, there is no reason to doubt the general validity of the measurements.

Regarding the question whether the measurements are representative of far-field conditions, the data for three different sizes of nozzle have been compared on Figures 8 and 9. The agreement among the results and the absence of change in the reductions measured over the range 21 to 32 nozzle diameters from the axis implies that even at the closest distance near-field effects are not significant.

It has not been possible to make such a direct comparison for the coaxial jets, but since the minimum measuring distance of 17 nozzle diameters is similar to that for the single-stream tests it has been assumed that the measurements are acceptable. Some substantiation for this view will be given later.

8.0 Theoretical considerations

Ideally, when measurements are made with the object of producing a prediction method, the range of parameters covered should be wide enough to avoid any extrapolation. However, the upper limit placed on both the jet and tunnel velocity in the present tests makes some extrapolation unavoidable. So that this may be carried out with some justification, the prediction method has been based on jet noise theory, following the approach used to correlate the data from the earlier tests. This allows the prediction method to be used up to the Mach wave regime (about 540 m/s) before other considerations apply.

In the report of the first series of tests it was concluded that a general expression for the effect of flight on the noise of a single-stream jet is:

$$\Delta OASPL' = \Delta OASPL - 10 \log_{10} (1 + M_a \cos\theta) + 10 \left(\omega_j - \omega_{rel}\right) \log_{10} \left(\frac{\rho_o}{\rho_j}\right) \quad \ldots.(1)$$

The noise reduction $\Delta OASPL$ can be calculated if

$$\Delta OASPL' = 10 \log_{10} \left[\left(\frac{V_j}{V_{rel}}\right)^m \frac{C_{Vj}}{C_{Vrel}}\right] \quad \ldots.(2)$$

and $$C = \left[(1 - M_c \cos\theta)^2 + 0.09 M_c^2\right]^{-p} \quad \ldots.(3)$$

using the notation detailed in Appendix I.

The subscript added to the convective amplification term C denotes the velocity at which it is to be evaluated, that is, using

$$M_c = 0.65 \frac{V_j}{a_o} \quad \text{or} \quad 0.65 \frac{V_{rel}}{a_o} \quad \ldots.(4)$$

To use these equations, the values of m and p must be established from tests with unheated jets, and the validity of the third (density dependent) term checked and modified if necessary.

The above equations are based on Ffowcs Williams' modification[12] of Lighthill's acoustic analogy[13]. The third (jet density) term was not derived theoretically, however, but arose from the experimental studies of the effect of jet temperature on jet noise[10,11]. These studies showed that jet temperature effects can be adequately correlated by $\left(\frac{\rho_j}{\rho_o}\right)^\omega$, where ω is dependent on jet velocity. This term is unrelated to the nature of the noise mechanisms; it merely quantifies in a simple form the overall influence of temperature sources, propagation effects, and modifications to the dynamics and structure of the jet due to jet temperature.

In the Appendix of Reference 2 an attempt was made to relate the value of m for unheated jets to changes in the jet structure and dynamics that occur in flight. If it is assumed that these effects are independent of jet temperature and that the value of ω depends on the relative jet velocity, V_{rel}, rather than on V_j, then the density dependent term in Equation (1) results. This term predicts that at low jet velocities the noise reductions

in flight will be smaller for a hot jet than for an unheated jet; the difference decreasing at higher jet velocities as ω tends to become constant with V_j. However, only a small effect of velocity, if any, is expected for the range of jet velocities studied during these tests.

9.0 Presentation and correlation of the single-stream data

9.1 Third-octave spectra

The spectra, already discussed in an earlier Section, indicate that the reductions in noise for the hot jet are similar over the whole frequency range. Although there is an apparent tendency for the reductions to be less at the high and low frequencies than in the mid range, the effect is not sufficiently positive to change the earlier conclusion of uniform reduction over the whole range. It follows from this that changes in spectrum level can be adequately described by the changes in the OASPLs, thereby simplifying the prediction method.

9.2 Overall noise levels

Figures 10 and 11 show the noise reductions with tunnel flow for the 65 mm diameter nozzle at a jet temperature of 880 K. All three jet velocities are shown and a comparison is made with the estimated line from all of the tests with the jet unheated. No attempt is being made to correlate the data at this stage but to ensure that any jet temperature effects are brought to light, the noise reductions are corrected for the influence of the wind-tunnel Mach number.

Ideally, to establish the importance of jet temperature (or more precisely, jet density) the experiments should be carried out over a range of jet temperatures and wind-tunnel velocities for a range of jet velocities. Unfortunately, it was not possible to explore such a wide range of variables during these tests and, therefore, the use of the data is limited to establishing first order effects.

The comparison made in these figures shows that the effects of jet temperature are generally small. Although there is a tendency for the heated jets to show slightly smaller noise reductions, the expected trend with the jet velocity has not emerged. Nevertheless, by taking together all of the data obtained from these experiments it is now possible to check the recommendations made in References 1 and 2 and, if necessary, modify them. Consideration will be given first to the data from the unheated jets and then to the effects of jet temperature.

9.2.1 Cold air jets

In the earlier tests the value of m (Equation (2)) was found to be 5.1 - this value is equal to the slope of the line drawn through the data taken at 90^{o} when presented as in Figure 9. It has already been concluded that the results obtained with various sizes of nozzle are similar, but a closer study shows that the line which best fits all the data has a slope m of 5.4 rather than 5.1.

It was suggested in Reference 2 that the tunnel reverberations slightly increased the value of m and the true value should have been less than that measured. But since it is now believed the noise reductions are not significantly influenced by reverberation, such a correction need not be considered and the value of 5.4 may be taken as substantially correct.

Further analysis has shown that p = 1.9, the value obtained from the first stage of tests, gives an acceptable correlation of the present data and so this value has remained unchanged.

9.2.2 Jet temperature effects

Using the data on Figures 10 and 11 it is now possible to quantify the effects of jet temperature. Considering the measurements at 90^{o} as an example, Figure 11 shows that the value of m changes from 5.4 for an unheated jet to about 4.6 at 880 K; it is not possible to give a precise value for the hot jet because of the scatter of the data. Although smaller noise reductions are expected as the jet temperature increases, a correlation of the data shows that temperature effects are much less than those expected from Equation (1). In fact, this correlation showed that the noise reductions due to temperature alone are approximately three-tenths of the anticipated value. Clearly, differences of this magnitude emphasise the simplicity of the assumptions underlying the jet density term. For present purposes, the term has been retained with an empirical coefficient to be used with the derived values of m and p to produce suitable equations for prediction. These are

$$\Delta OASPL' = \Delta OASPL - 10 \log_{10} (1 + M_a \cos \theta) + 3 \left(\omega_j - \omega_{rel}\right) \log_{10} \frac{\rho_o}{\rho_j} \quad \ldots.(5)$$

where now

$$\Delta OASPL' = 10 \log_{10} \left[\left(\frac{V_j}{V_{rel}}\right)^{5 \cdot 4} \frac{C_{Vj}}{C_{Vrel}}\right] \quad \ldots.(6)$$

and as before

$$C = \left[(1 - M_c \cos \theta)^2 + 0.09 M_c^2\right]^{-1 \cdot 9} \qquad \ldots.(7)$$

The noise reductions predicted from these equations showed acceptable agreement with the measurements at 90° and in the rear-arc, but in the forward-arc, particularly at 120°, the noise reductions were underpredicted. However, following a previous suggestion[2] that the noise reductions in this region are the same as those at 90°, other than for the Doppler factor due to the wind-tunnel Mach number, then

$$\Delta OASPL' = 10 \log_{10} \left(\frac{V_j}{V_{rel}}\right)^{5 \cdot 4} \qquad \ldots.(8)$$

can replace Equation (6) for angles above 90°.

Using the above equations, a comparison between the predicted and measured noise reductions is presented in Figures 12 and 13. Ideally, all data points should lie on the line drawn with a slope of unity. Despite the fact that there is not a perfect collapse of the data, it is considered that the method is wholly acceptable for prediction and is a step forward in quantifying of the effect of flight on aircraft noise.

In conclusion, the points made in this Section may be summarised as follows. Equations (5), (6) and (7) should be used for prediction at 90° and in the rear-arc, whereas Equations (5) and (8) should be used for angles up to 120° in the forward-arc. It is not possible to recommend the use of the equations at angles above 120° as the predictions have yet to be verified in this region. Finally, the equations are suitable for both OASPLs and spectra.

10.0 Coaxial jet noise

At first sight it would seem that an accurate and simple prediction method for coaxial jets would be complicated by the number of variables involved. Because of this, and to put the prediction method on a firm footing, the correlations of the data produced during the first stage of tests[2] were made with the noise generation processes in mind. The method was based on the concept that the noise produced by each stream could be considered separately, and although this idea produced a satisfactory correlation of a limited range of noise data, the universal validity of the suggestion needed further substantiation. The additional data taken during

the recent tests have shown that the concept was over-simplified and that a more fundamental understanding of the noise generation processes is required before the data can be treated in this manner.

For the present, therefore, the basis of the prediction method will be simplified by exploiting the observation[14] that the noise reductions of coaxial jets are independent of the secondary flow velocity. Before coming to the details of the correlation some typical spectra will be shown.

10.1 Third-octave spectra

Typical spectrum levels with and without tunnel flow are shown in Figure 14. As before, distortions in the spectral shape can be seen, but likewise they are not believed to be of consequence since the noise reductions in the regions of distortion are similar to those in other parts of the spectra. The main conclusion from these figures is that for practical purposes the noise reductions are the same at all frequencies and hence the reductions in spectrum level can be considered in terms of the OASPLs, as for the single-stream jets.

10.2 Overall noise levels

If the noise reductions for coaxial jets are independent of the by-pass flow conditions then a satisfactory correlation should be produced by the equations evolved for single-stream jets, with the primary jet velocity as the dependent parameter. To examine this point, in Figures 15 and 16 the measured noise reductions are compared with those predicted for an unheated jet (that is, by omitting the jet density term from Equation (5)). This term was omitted because a comparison of the data showed that very similar noise reductions occurred for both unheated and heated primary jets. Although there is some scatter in the data and a tendency for the noise reductions to be over-predicted, it is nevertheless remarkable that this arbitrary prediction method produces such a good data collapse, especially when it is considered that both jet velocity and velocity ratio were varied over a wide range. It is interesting that the data can be correlated in this way; for it had been expected that at the velocity ratios tested here, the noise would be dominated by the secondary flow and this would be a significant correlating parameter. However, attempts to introduce this as a parameter in the prediction method failed.

Although Figures 15 and 16 show that an acceptable prediction method has been evolved, it must be remembered that the correlation has neither a physical nor a theoretical basis and consequently extrapolation outside the limits of the data should be treated with caution.

10.3 The effect of nozzle area ratio

The coaxial jet data presented up to now were obtained at an area ratio of 2.5. Since this is a typical value for high by-pass ratio engines and since satisfactory data correlations have been achieved without considering the by-pass flow velocity, it is reasonable to assume that the suggested prediction method is suitable for general aircraft assessments when the by-pass area ratio is approximately 2.5. The existence of data at an area ratio of 2.0 from the earlier phase of tests invited a comparison with the present data and a check of this assumption.

At first sight it seems reasonable to conclude from the comparison shown in Figures 17 and 18 that the smaller area ratio nozzle has lower noise reductions. However, the microphone traverse distance in the tests at area ratio 2.0 was 12 secondary nozzle diameters whereas it was 17 diameters in the tests at area ratio 2.5. It seems, therefore, possible that the apparent differences may be due to near-field effects rather than to the difference in area ratio, and it must be concluded that further work is necessary to establish the importance of secondary nozzle area ratio.

For the present, the data obtained at the nearer traverse distance at area ratio 2.0 will be discounted, and the prediction based on Figures 15 and 16 will be assumed to apply to all area ratios to be met in practice. The inference from Figures 17 and 18 is that this assumption does not give rise to a large uncertainty in the predicted level.

11.0 Conclusions

Using data from experiments in a wind-tunnel, methods have been evolved for predicting the effect of flight on both single-stream and coaxial jets. A completely general application of the proposed methods is constrained by a number of factors; in particular, the maximum tunnel and jet velocities were less than those required to avoid extrapolation for typical aircraft assessments. For single-stream jets, extrapolation up to jet velocities near the Mach wave regime (about 540 m/s) may be carried out with some justification since the prediction method is based on jet noise theory modified by experimentally-derived constants. However, for coaxial jets, the recommended prediction method is wholly empirical and any extrapolation must be treated with caution.

All of the data used in the analysis are believed to be of acceptable quality even though the spectra were distorted to some degree by reverberent sound at low frequencies and for an unknown reason at high frequencies. An assessment shows that the high frequency distortion is not caused by rig noise.

An analysis of data from tests with nozzles of various diameters strongly indicates that any near-field effects are small and that the prediction methods produce acceptable far-field estimates.

The noise reductions, which are smallest in the forward-arc, increase steadily for both single-stream and coaxial jets as the angle approaches zero.

For single-stream jets flight causes only slight changes in the observed spectral shapes. Therefore, the method recommended for the prediction of the changes in the OASPLs may also be applied to the spectrum levels.

Slightly smaller reductions in OASPL were observed for hot jets; e.g. at 90^{o} the relative velocity exponent changes from 5.4 for unheated jets to about 4.6 at a jet temperature of 880 K.

For coaxial jets the noise reductions were found to be independent of secondary flow velocity. The reductions were found to correspond to those predicted for unheated single-stream jets at a jet velocity equal to that of the primary stream. As for single-stream jets, flight caused only slight changes in the spectrum shape.

Variation in secondary nozzle area ratio over the range 2.0 to 2.5 had only a small effect on the noise reduction caused by forward speed. Further work is needed to quantify the importance of this parameter precisely.

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APPENDIX I

Notation

SI Units are used unless otherwise stated

a_o	ambient speed of sound
A	area of single-stream jet
C	convective amplification term defined by Equation (3); suffix used to denote its value at a particular velocity
D	diameter of single-stream nozzle
f	frequency
M_a	wind-tunnel Mach number
M_c	eddy convection Mach number
m	relative velocity exponent in Equation (1)
OASPL	overall sound pressure level (dB re 20μN/m)
OASPL'	normalised overall sound pressure level (dB re 20μN/m)
p	exponent of convective amplification in Equation (3)
R	distance from microphone to centre of nozzle exit
SPL	sound pressure level (dB re 20μN/m)
T_j	total temperature of single-stream jet
T_p	total temperature of primary stream of coaxial jet
V_a	wind-tunnel velocity (m/s)
V_j	velocity of single-stream jet (m/s)
V_p	velocity of primary stream of coaxial jet (m/s)
V_{rel}	relative jet velocity ($V_j - V_a$) (m/s)
V_s	velocity of secondary stream of coaxial jet (m/s)
V_{To}	tunnel velocity with fan stationary (m/s)
Δ	denotes 'change in'
ρ_o	density of ambient air
ρ_j	fully expanded density of single-stream jet
θ	noise emission angle relative to jet axis
ω	jet density exponent
ω_j	jet density exponent at a jet velocity of V_j
ω_{rel}	jet density exponent at jet velocity of V_{rel}

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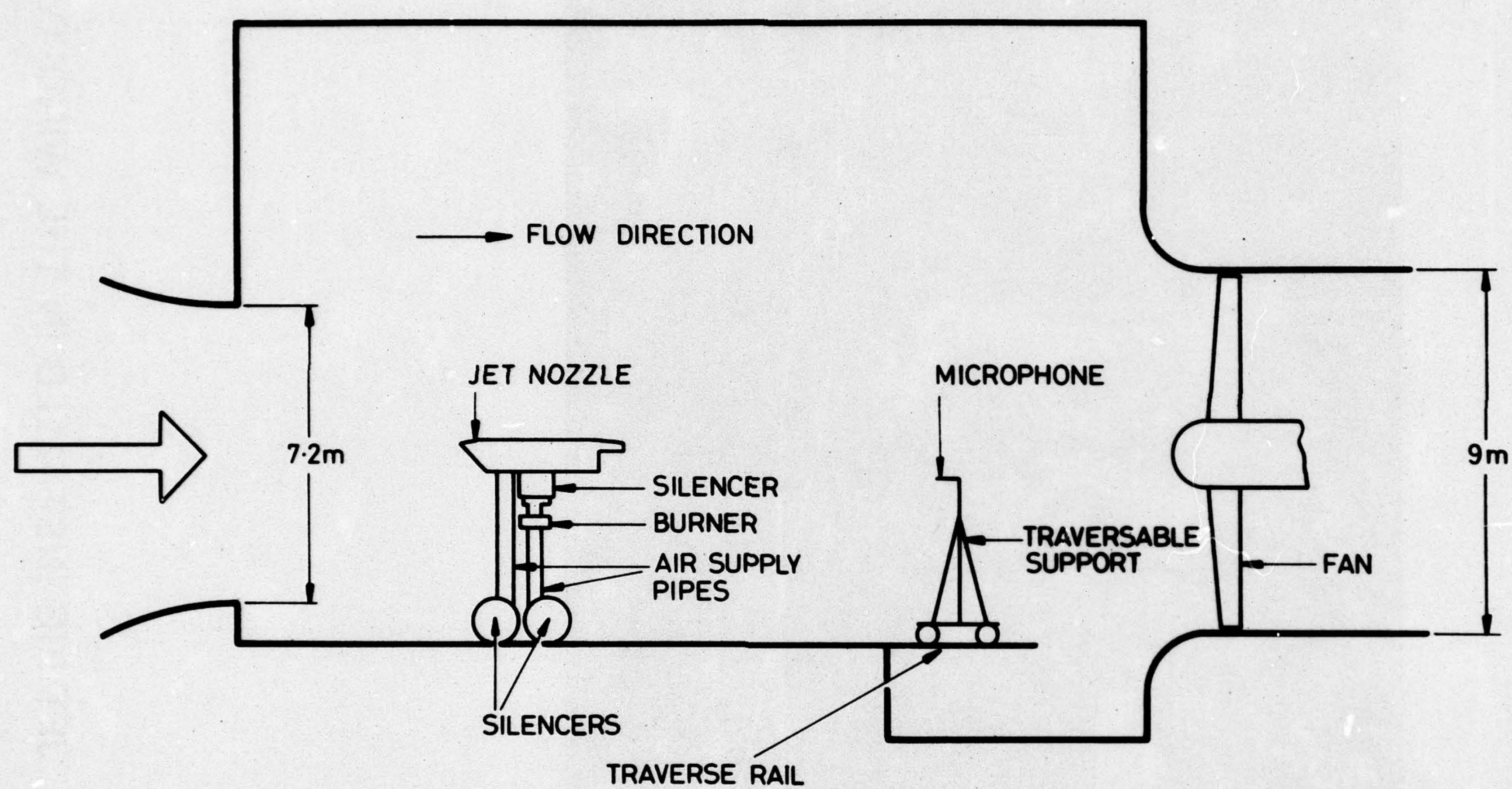


FIG.1 ARRANGEMENT OF RIG IN WIND-TUNNEL

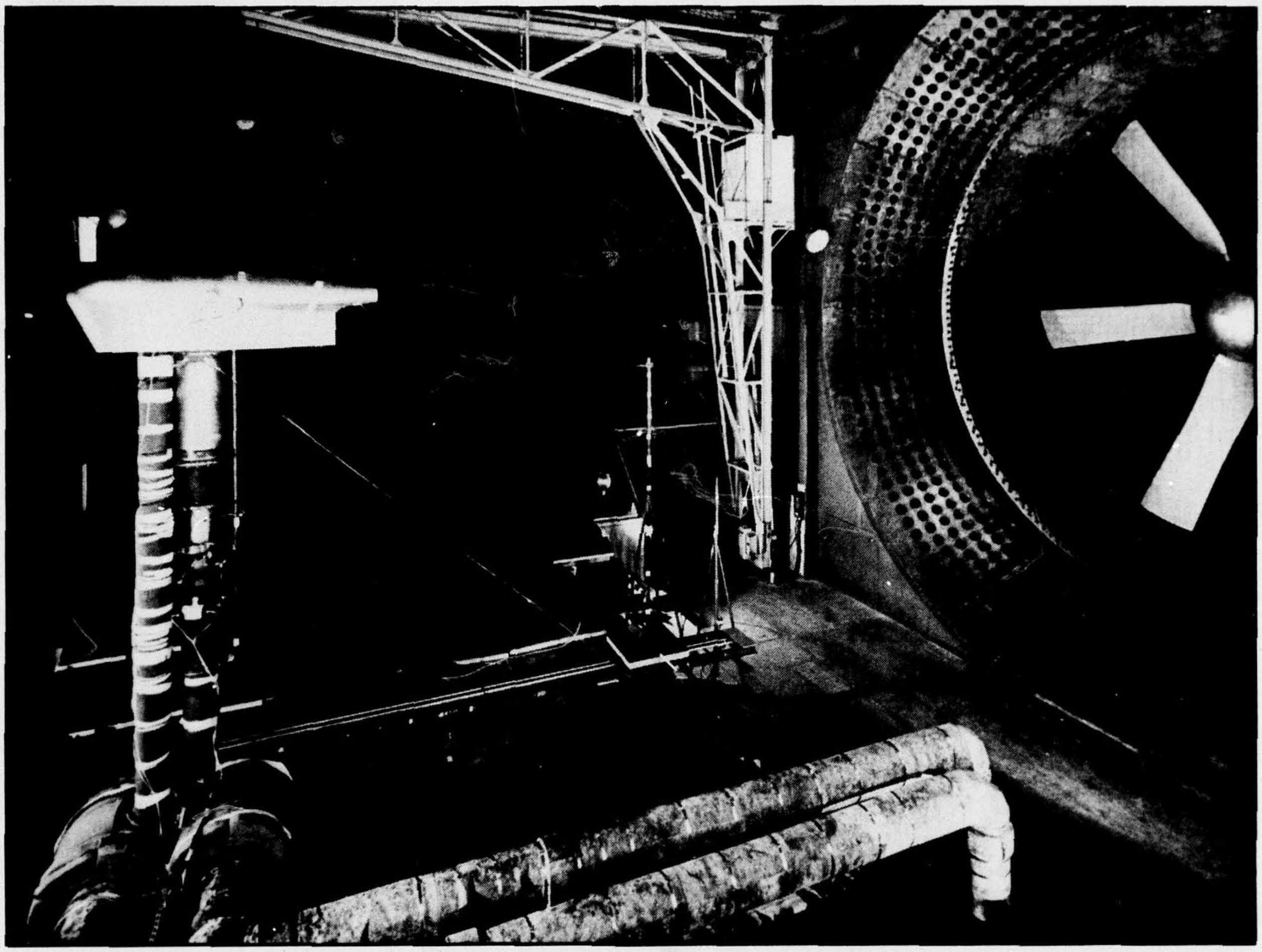


FIG.2 THE JET RIG INSTALLED IN THE WIND-TUNNEL

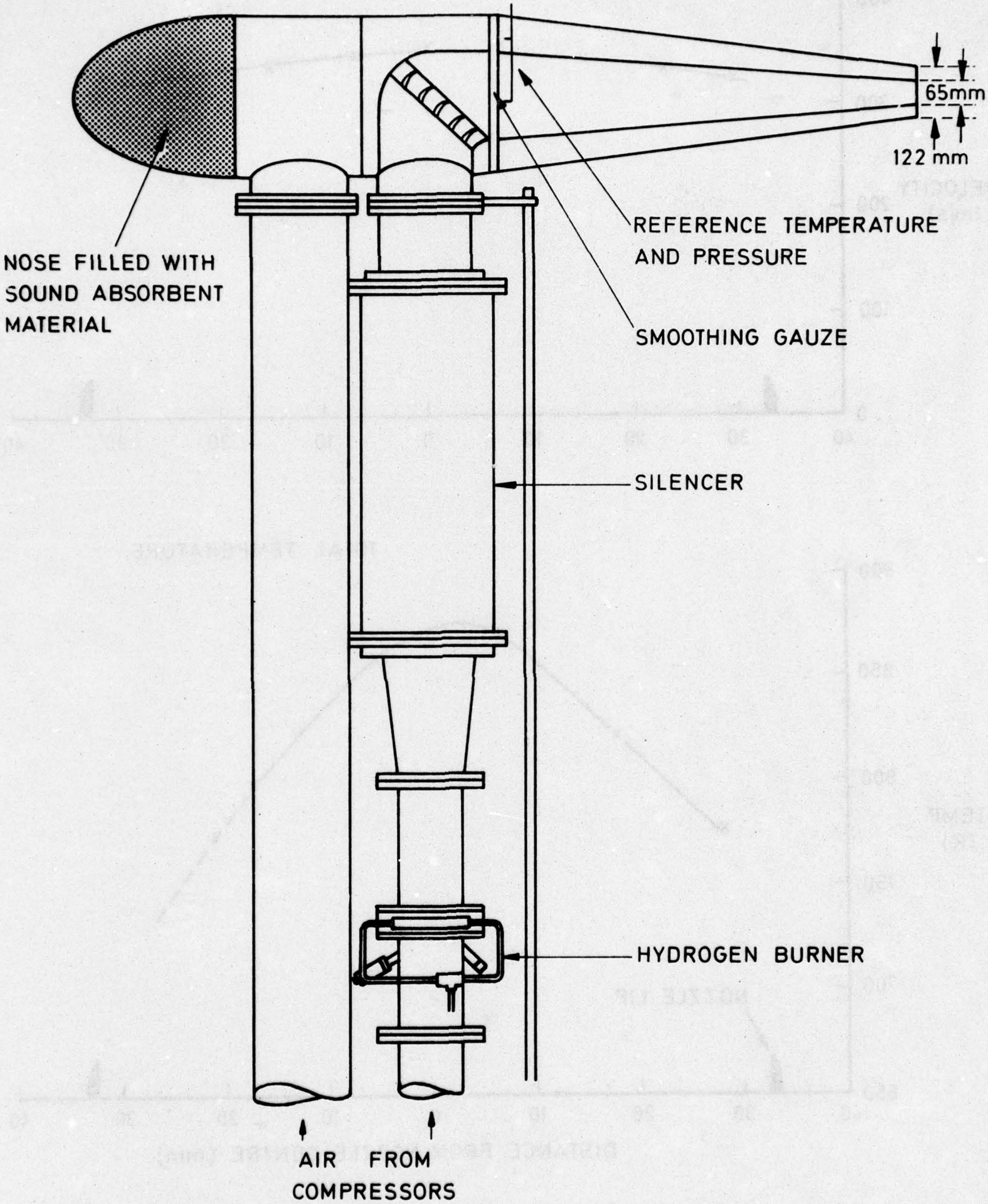


FIG. 3 CROSS-SECTION OF COAXIAL RIG

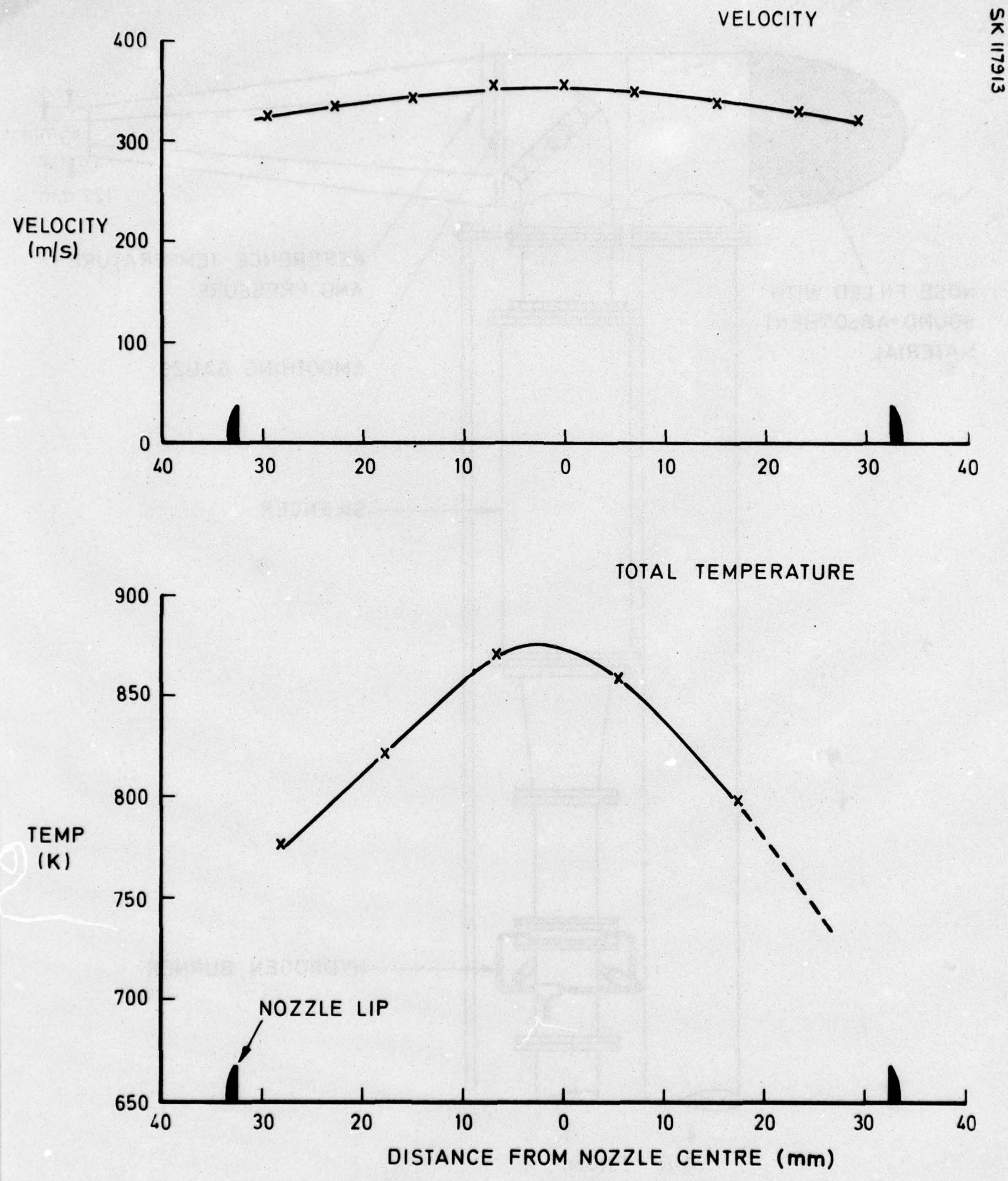
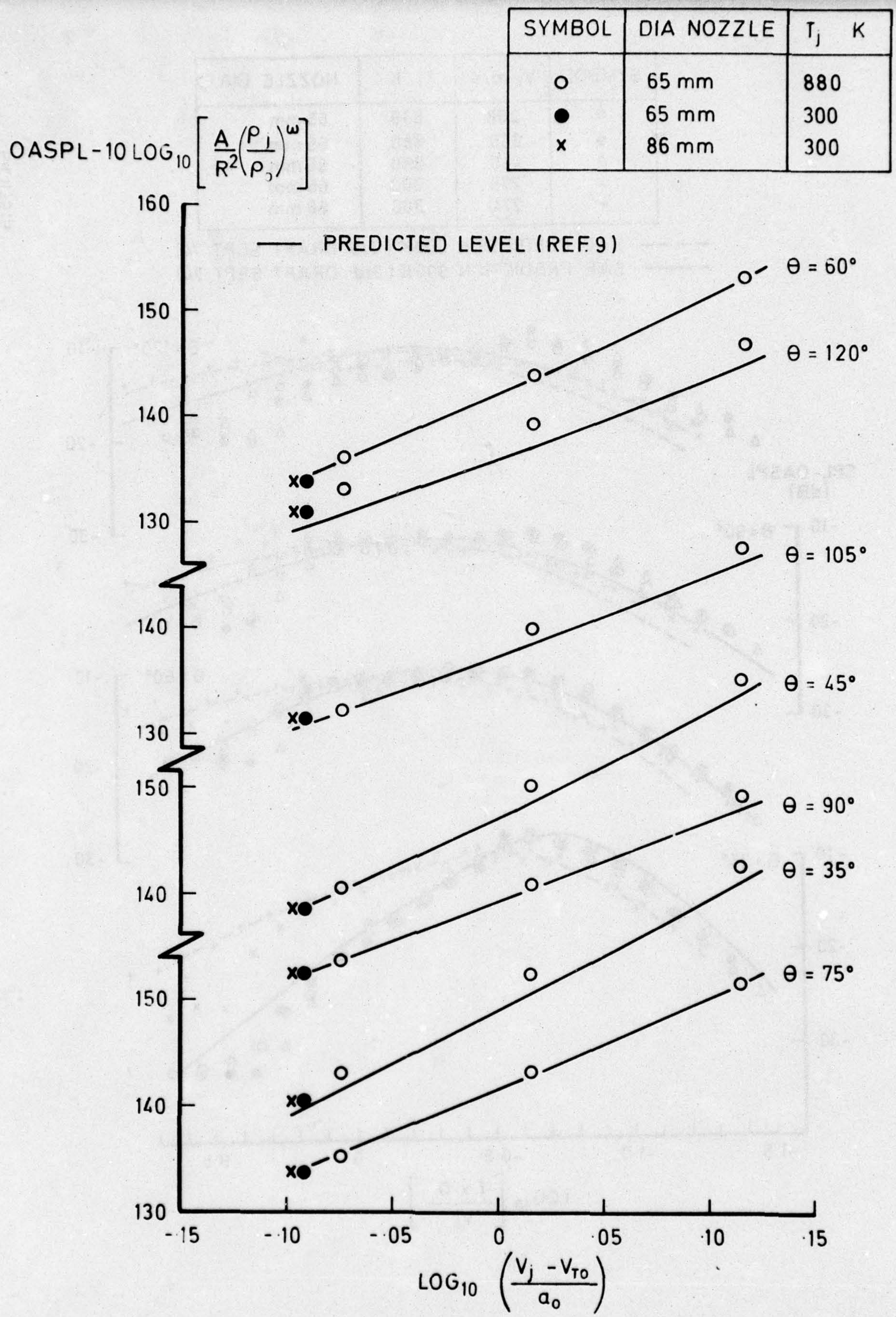


FIG. 4 SINGLE JET; TYPICAL TEMPERATURE AND VELOCITY PROFILES



SK 117914

FIG. 5 SINGLE JET; NORMALISED STATIC JET NOISE

SK 117915

SYMBOL	Vj m/s	Tj K	NOZZLE DIA.
o	288	880	65 mm
●	355	880	65 mm
Δ	446	880	65 mm
x	275	300	65 mm
+	274	300	86 mm

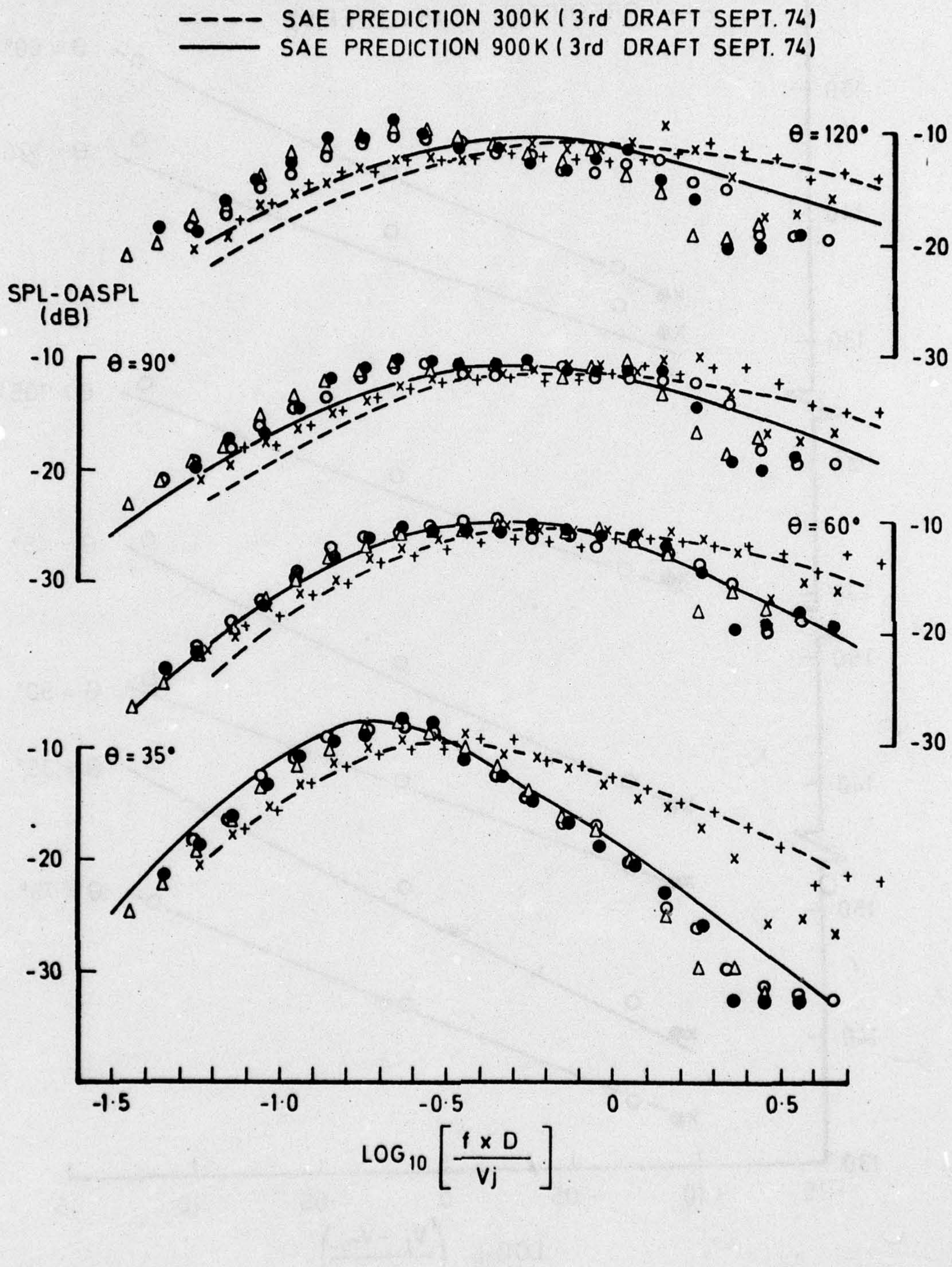


FIG. 6 SINGLE JET; THIRD OCTAVE SPECTRA MEASURED UNDER STATIC CONDITIONS

SK 117916

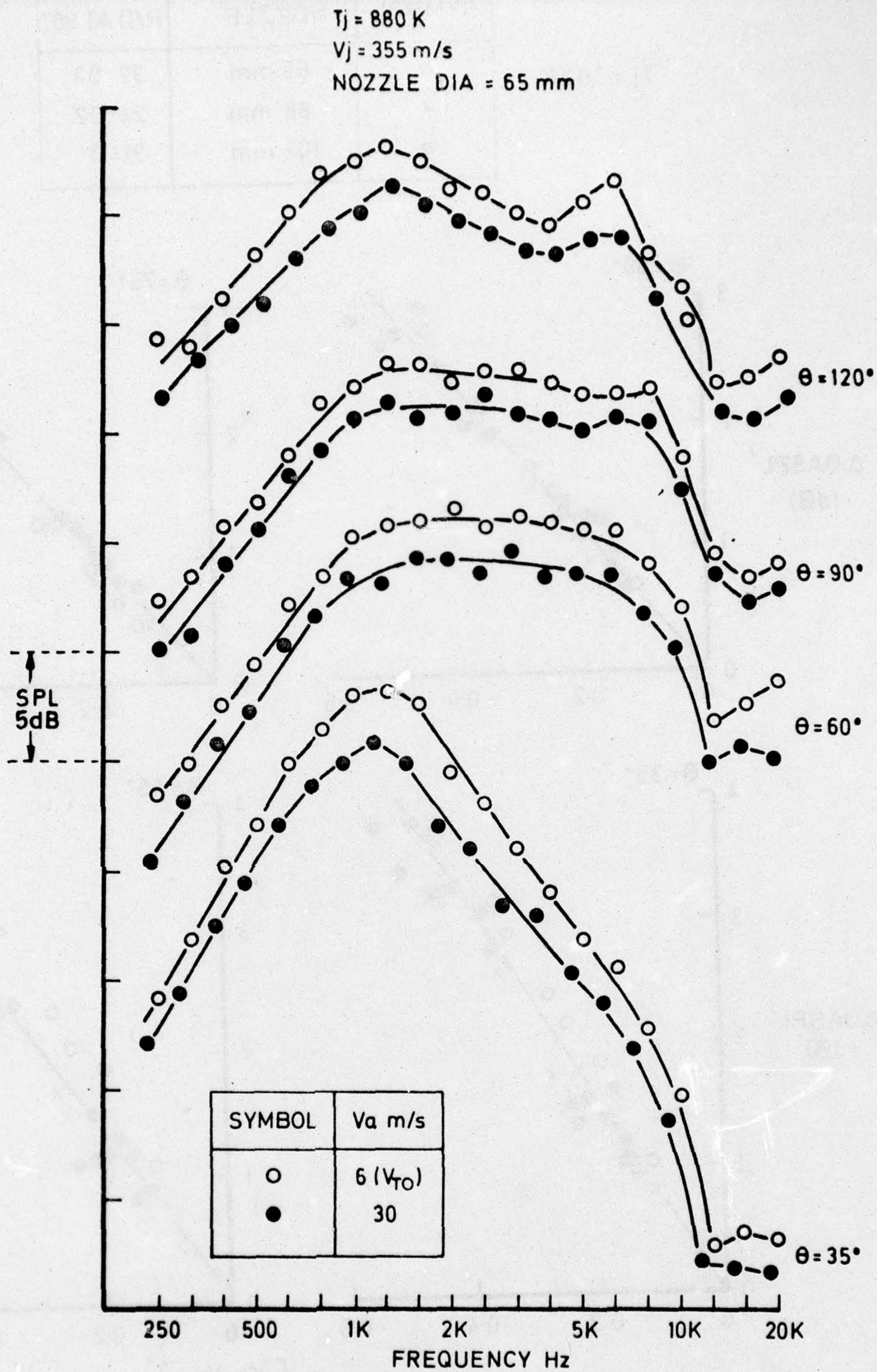


FIG.7 SINGLE JET ; HEATED, TYPICAL THIRD-OCTAVE SPECTRA WITH TUNNEL FLOW

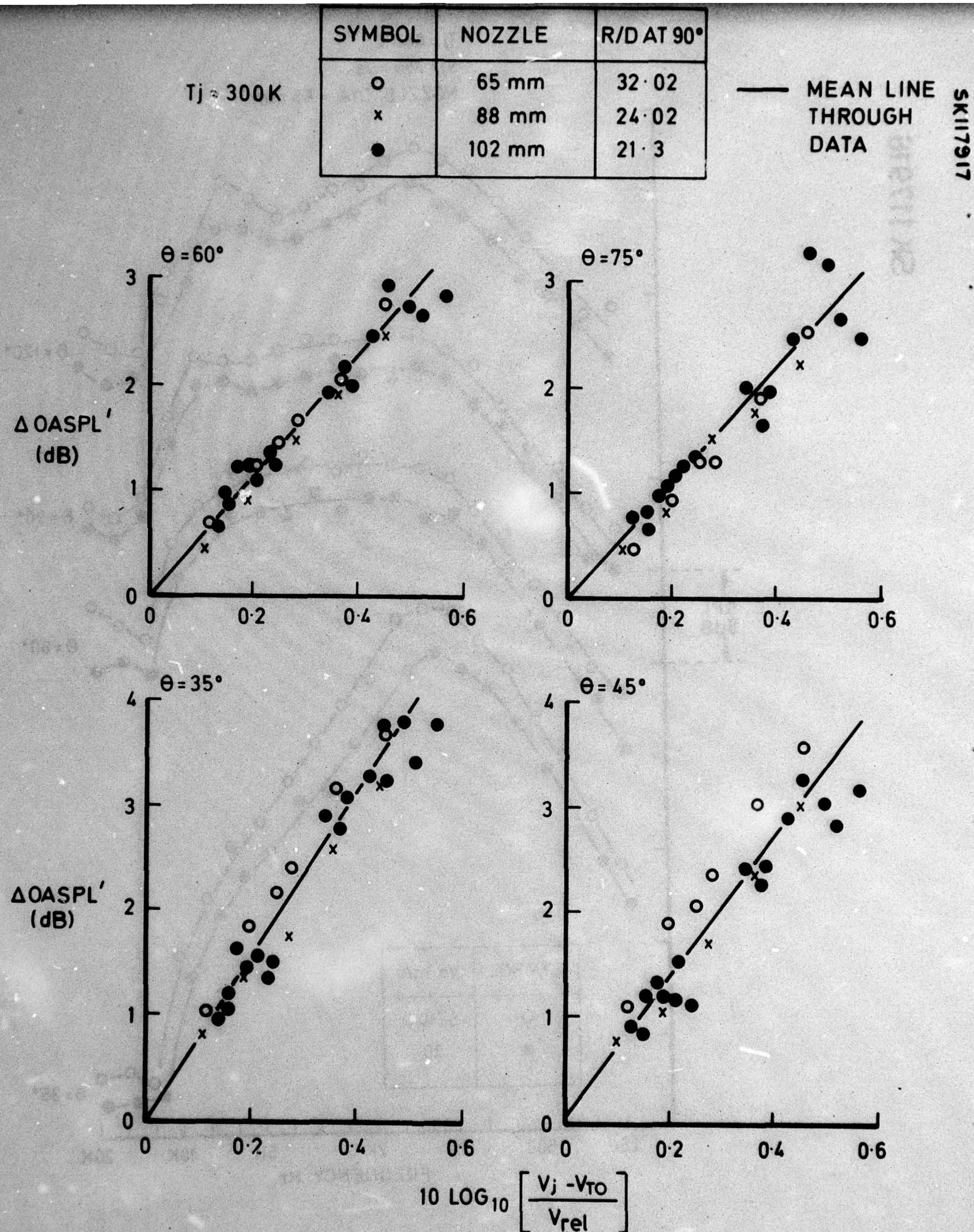


FIG. 8 SINGLE JET; UNHEATED, OASPL REDUCTIONS WITH TUNNEL FLOW, θ = 35°, 45°, 60°, AND 75°

Tj = 300K

SYMBOL	NOZZLE	R/D AT 90°
o	65 mm	32·02
x	88 mm	24·02
●	102 mm	21·3

—— MEAN LINE THROUGH DATA

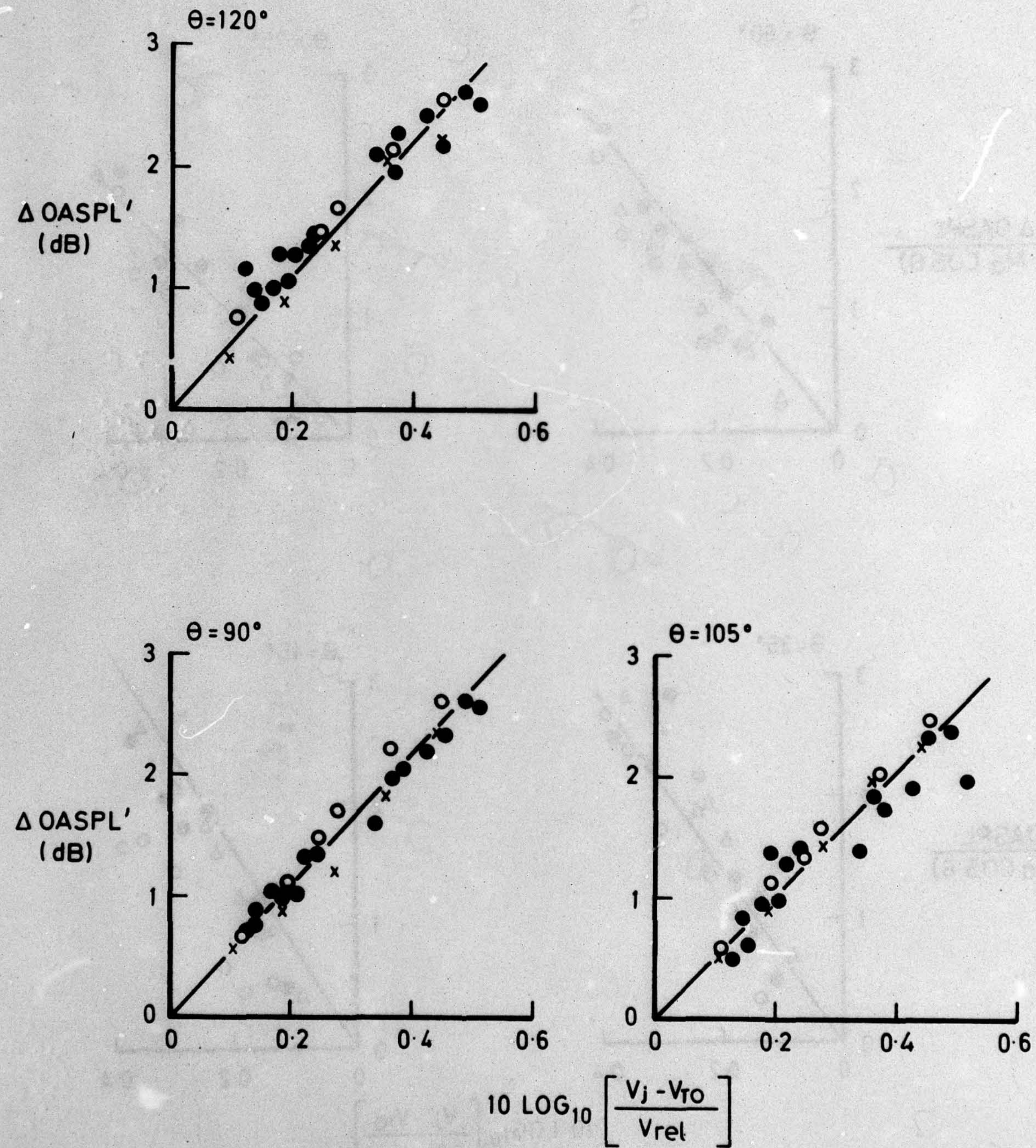


FIG. 9 SINGLE JET; UNHEATED, OASPL REDUCTIONS WITH TUNNEL FLOW, θ = 90°, 105°, AND 120°

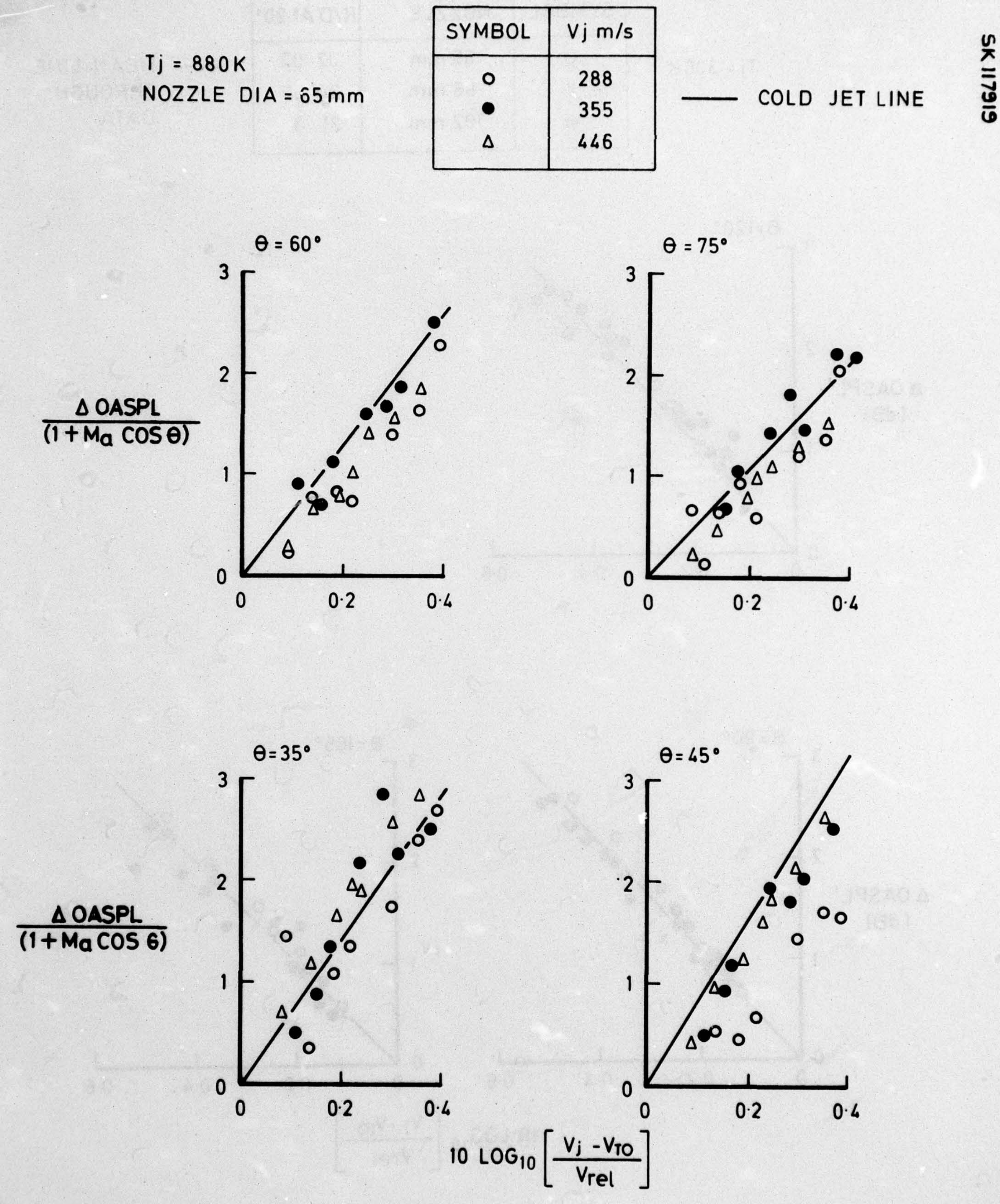


FIG.10 SINGLE JET; HEATED, NOISE REDUCTIONS WITH TUNNEL FLOW, θ = 35°, 45°, 60°, AND 75°

SK 11/920

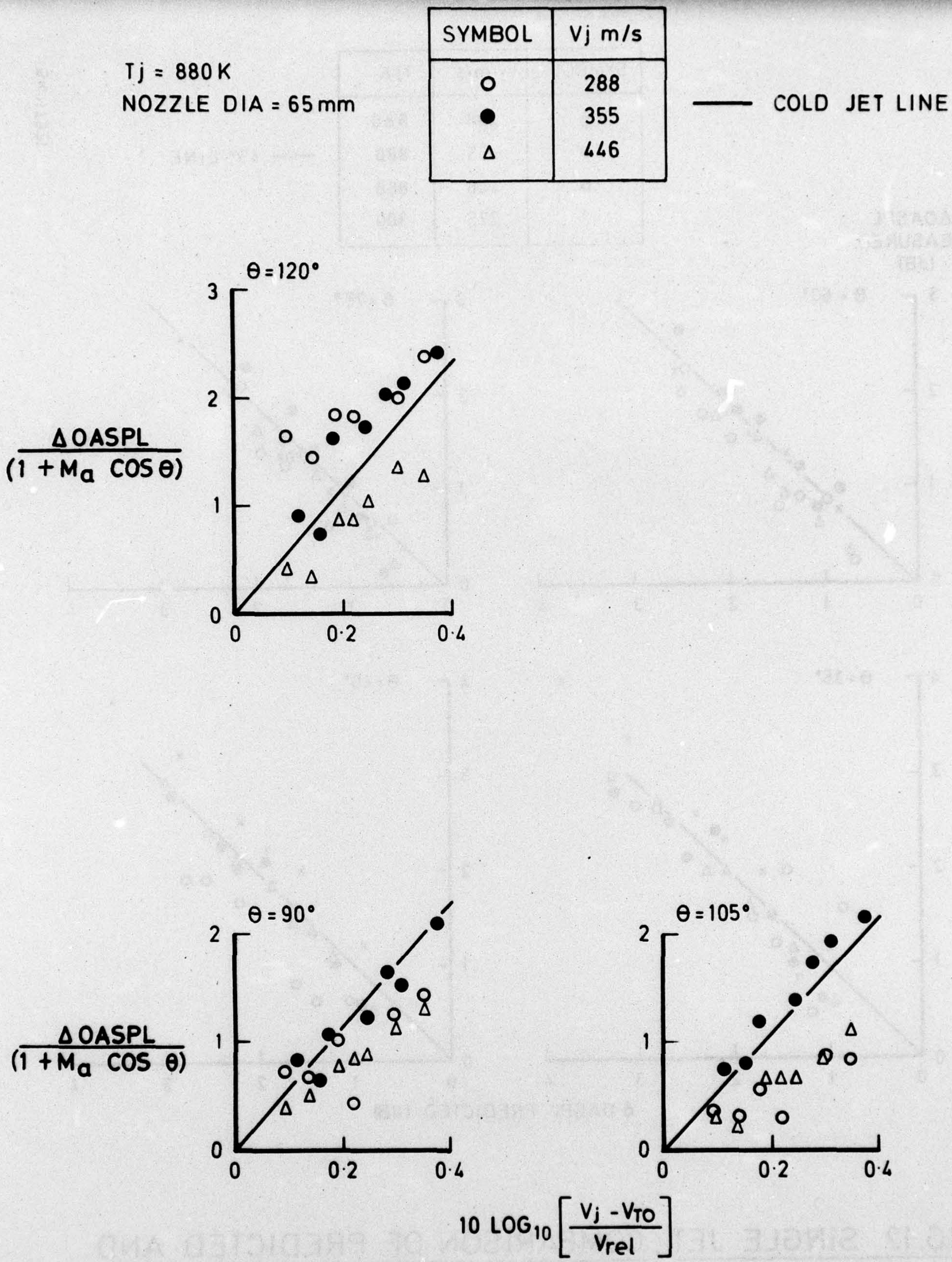


FIG. 11 SINGLE JET; HEATED, NOISE REDUCTIONS WITH TUNNEL FLOW, θ = 90°, 105°, AND 120°

SK 117921

SYMBOL	Vj m/s	Tj K
○	288	880
●	355	880
△	446	880
×	275	300

— 45° LINE

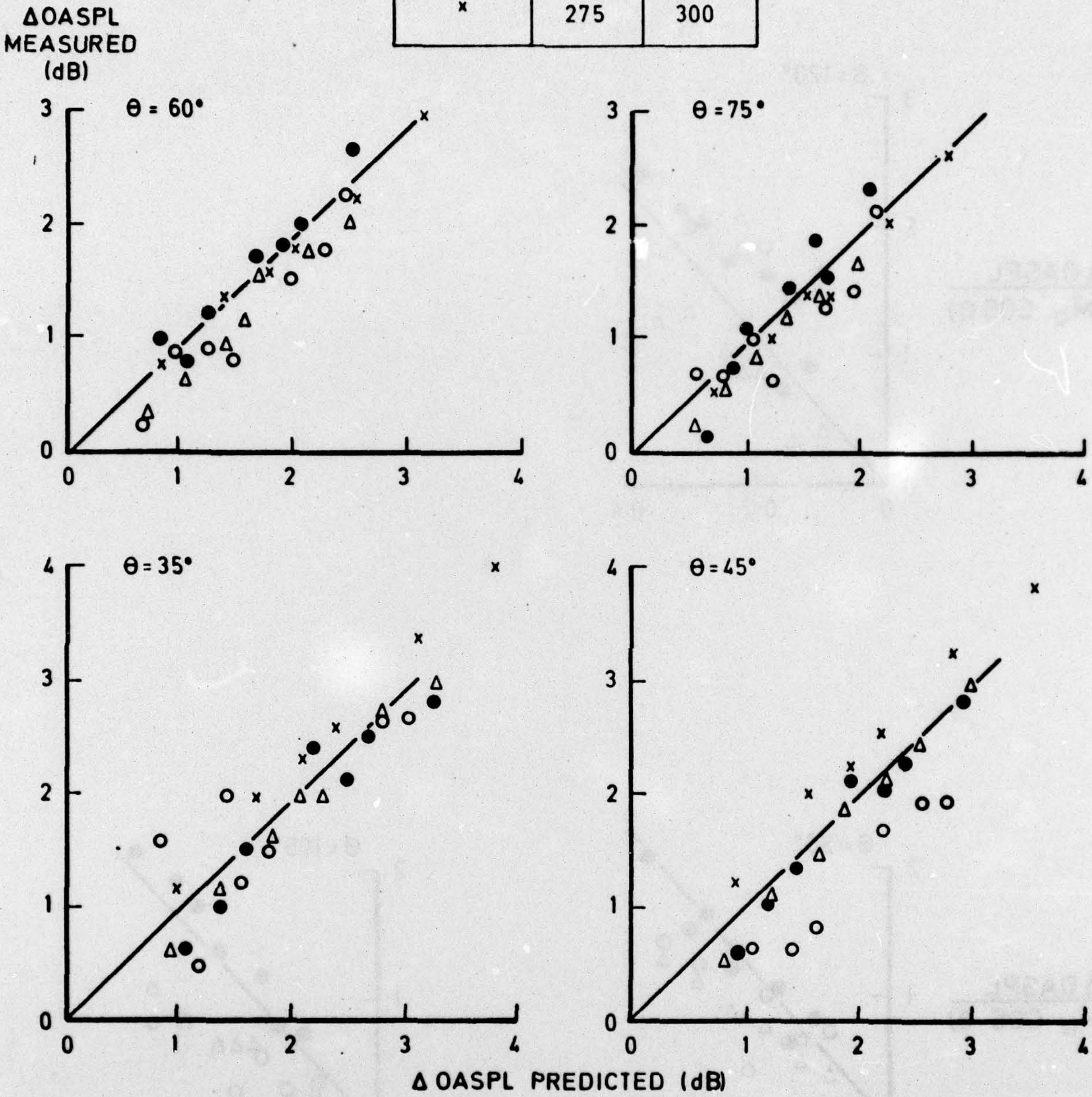


FIG. 12 SINGLE JET; COMPARISON OF PREDICTED AND MEASURED NOISE REDUCTIONS, θ = 35°, 45°, 60° AND 75°

SK 117922

SYMBOL	Vj m/s	Tj K
○	288	880
●	355	880
Δ	446	880
×	275	300

— 45° LINE

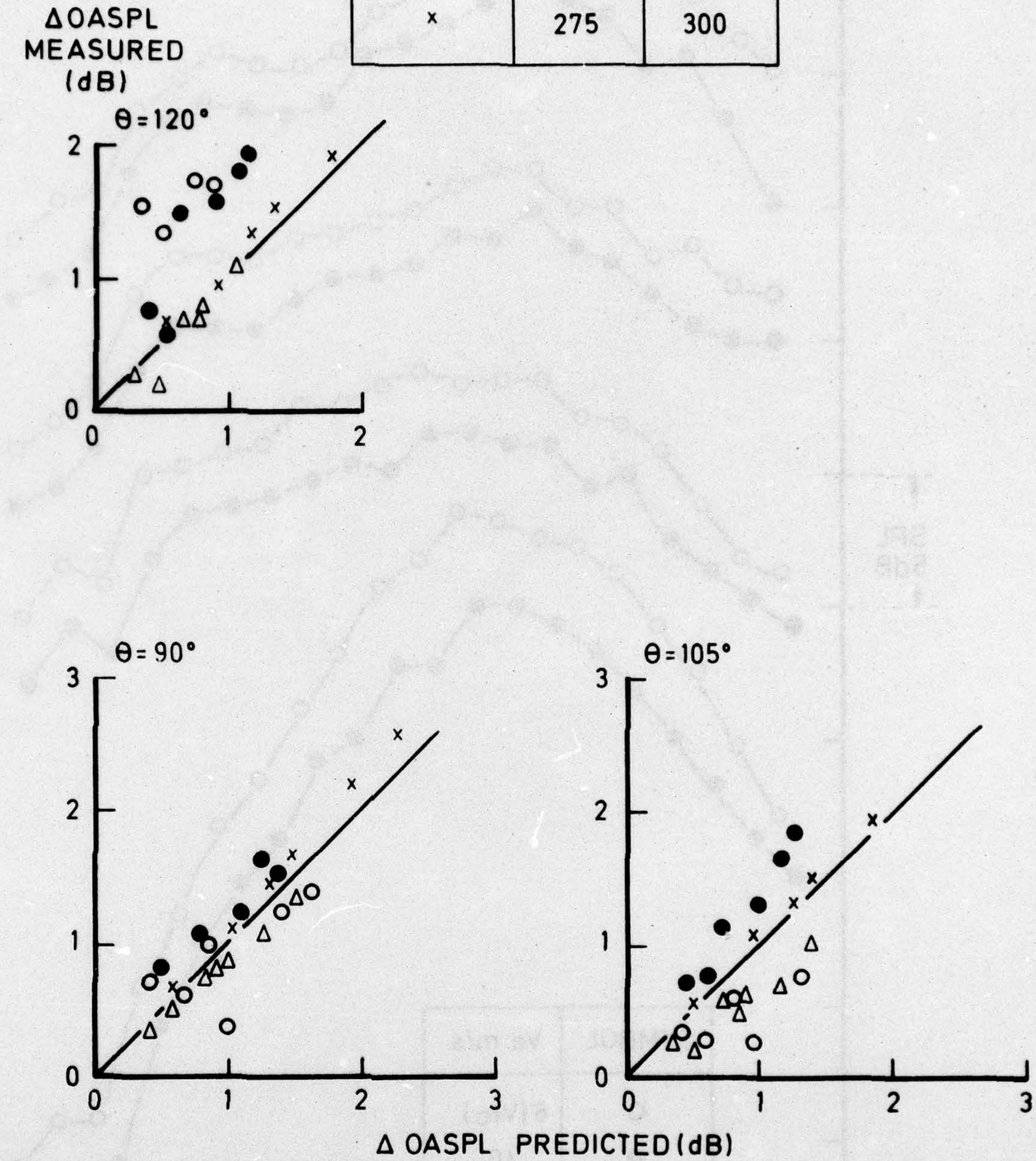


FIG. 13 SINGLE JET, COMPARISON OF PREDICTED AND MEASURED NOISE REDUCTIONS, θ = 90°, 105°, AND 120°

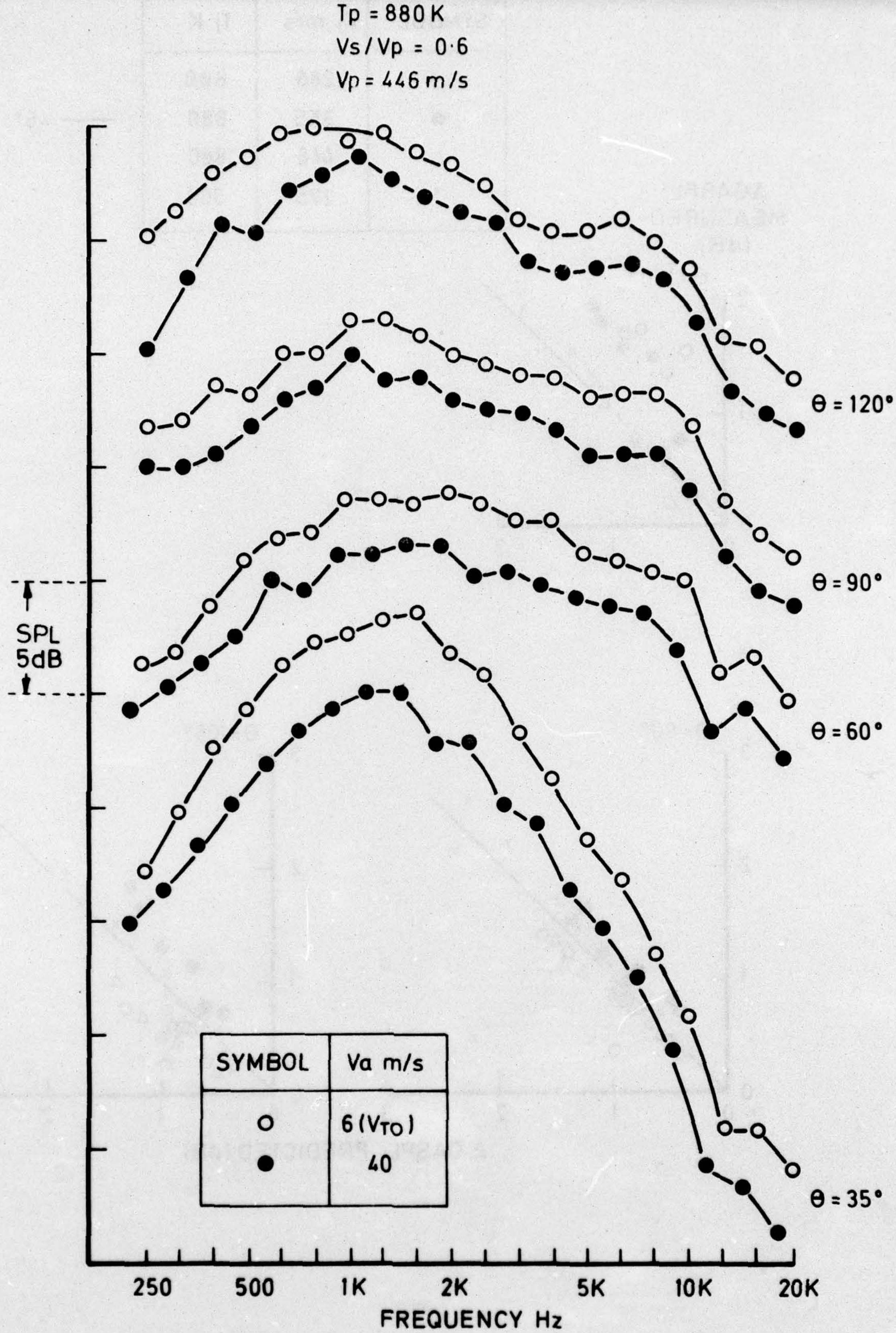


FIG.14 COAXIAL JET; HEATED PRIMARY, TYPICAL THIRD-OCTAVE SPECTRA WITH TUNNEL FLOW

SK 117924

SYMBOL	Vp m/s	Vs / Vp
x	286	1·0
○	286	0·6
□	286	0·8
△	447	0·6
▽	355	0·9
●	355	0·8
■	355	0·6

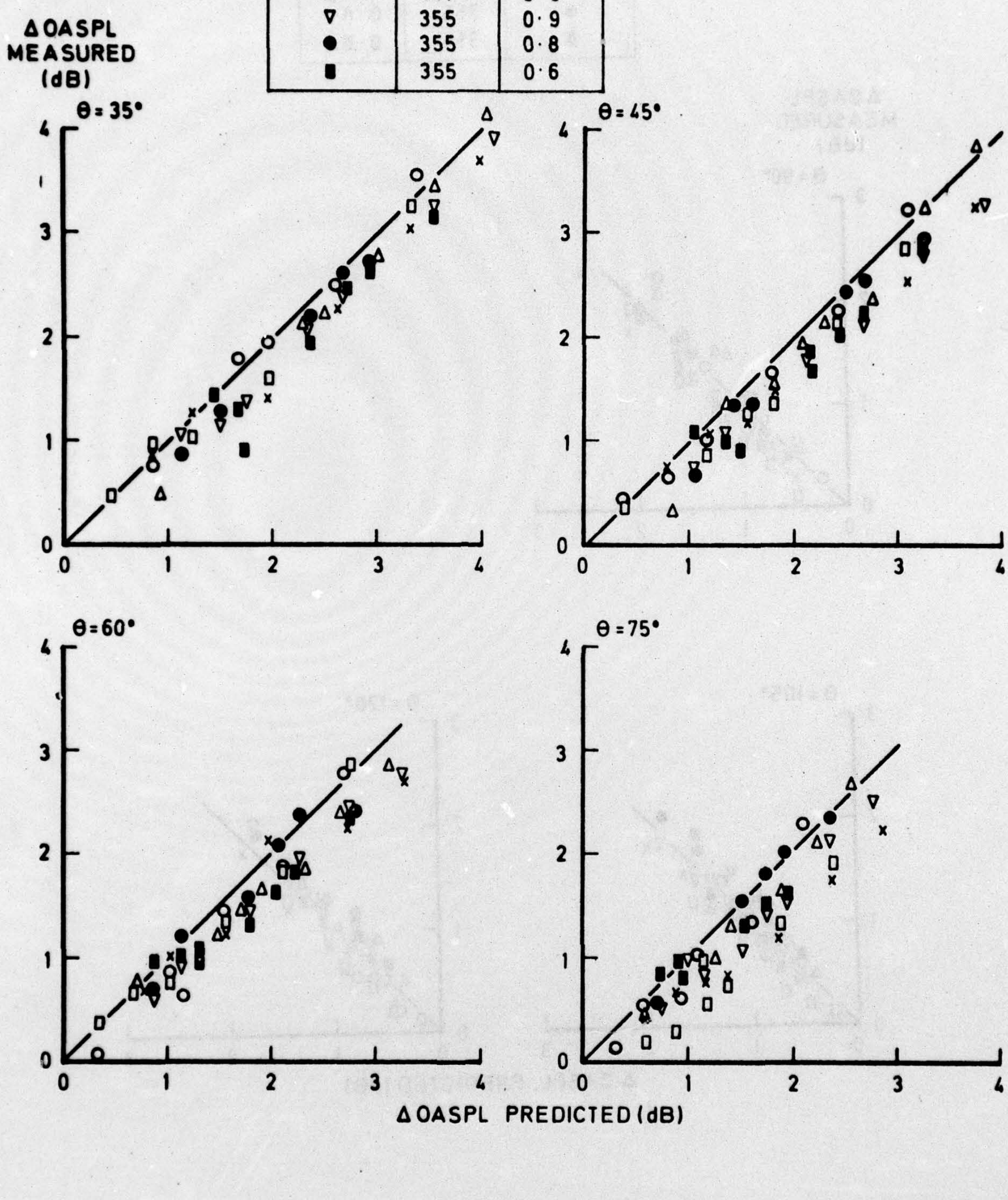


FIG. 15 COAXIAL JET; HEATED PRIMARY, COMPARISON OF PREDICTED AND MEASURED NOISE REDUCTIONS, θ = 35°, 45°, 60° AND 75°

SYMBOL	Vp m/s	Vs/Vp
×	286	1·0
○	286	0·6
□	286	0·8
△	447	0·6
▽	355	0·9
●	355	0·8
■	355	0·6

— 45° LINE

SK 117925

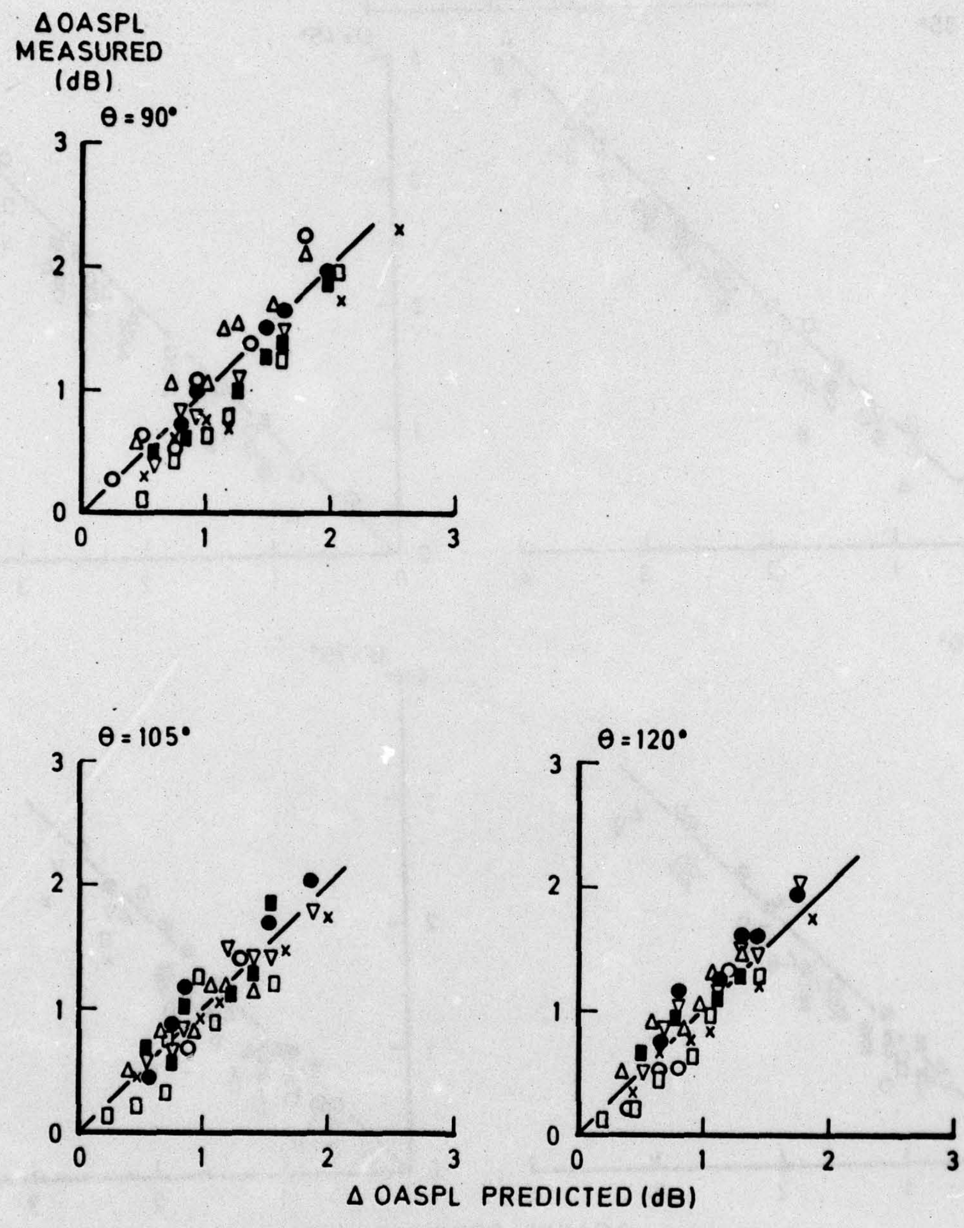


FIG. 16 COAXIAL JET; HEATED PRIMARY, COMPARISON OF PREDICTED AND MEASURED NOISE REDUCTIONS, θ = 90°, 105°, AND 120°

SK117926

T_p = 300 K

SYMBOL	Vp m/s	Vs/Vp	AREA RATIO
○	276	1·0	2·5
△	276	0·8	2·5
▽	276	0·6	2·5
●	244	0·7	2·0
▲	305	0·6	2·0
▼	305	0·5	2·0

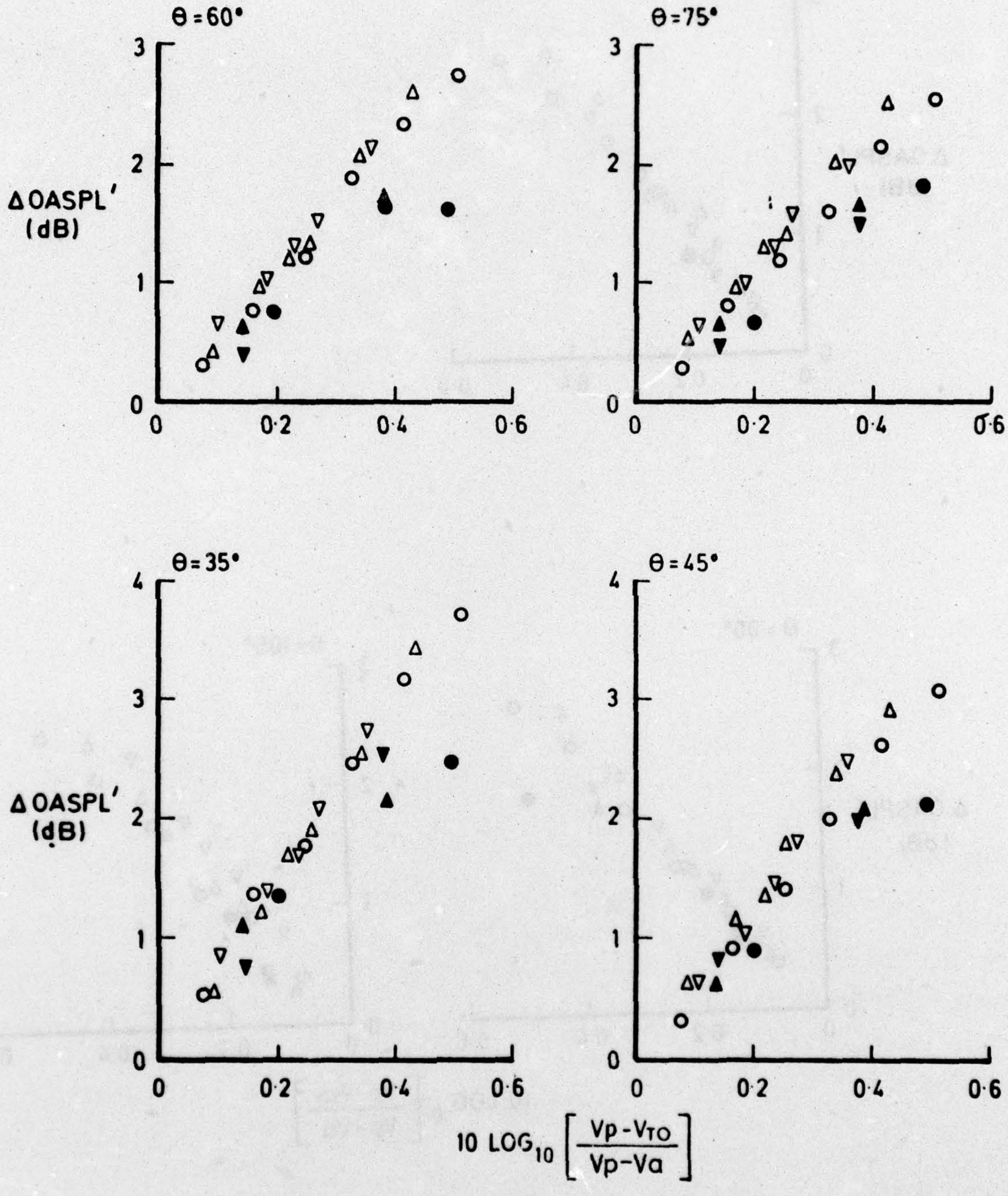


FIG. 17 COAXIAL JET; UNHEATED PRIMARY, THE EFFECT OF AREA RATIO, θ = 35°, 45°, 60° AND 75°

SYMBOL	Vp m/s	Vs/Vp	AREA RATIO
○	276	1·0	2·5
△	276	0·8	2·5
▽	276	0·6	2·5
●	244	0·7	2·0
▲	305	0·6	2·0
▼	305	0·5	2·0

Tp = 300K

SK 117927

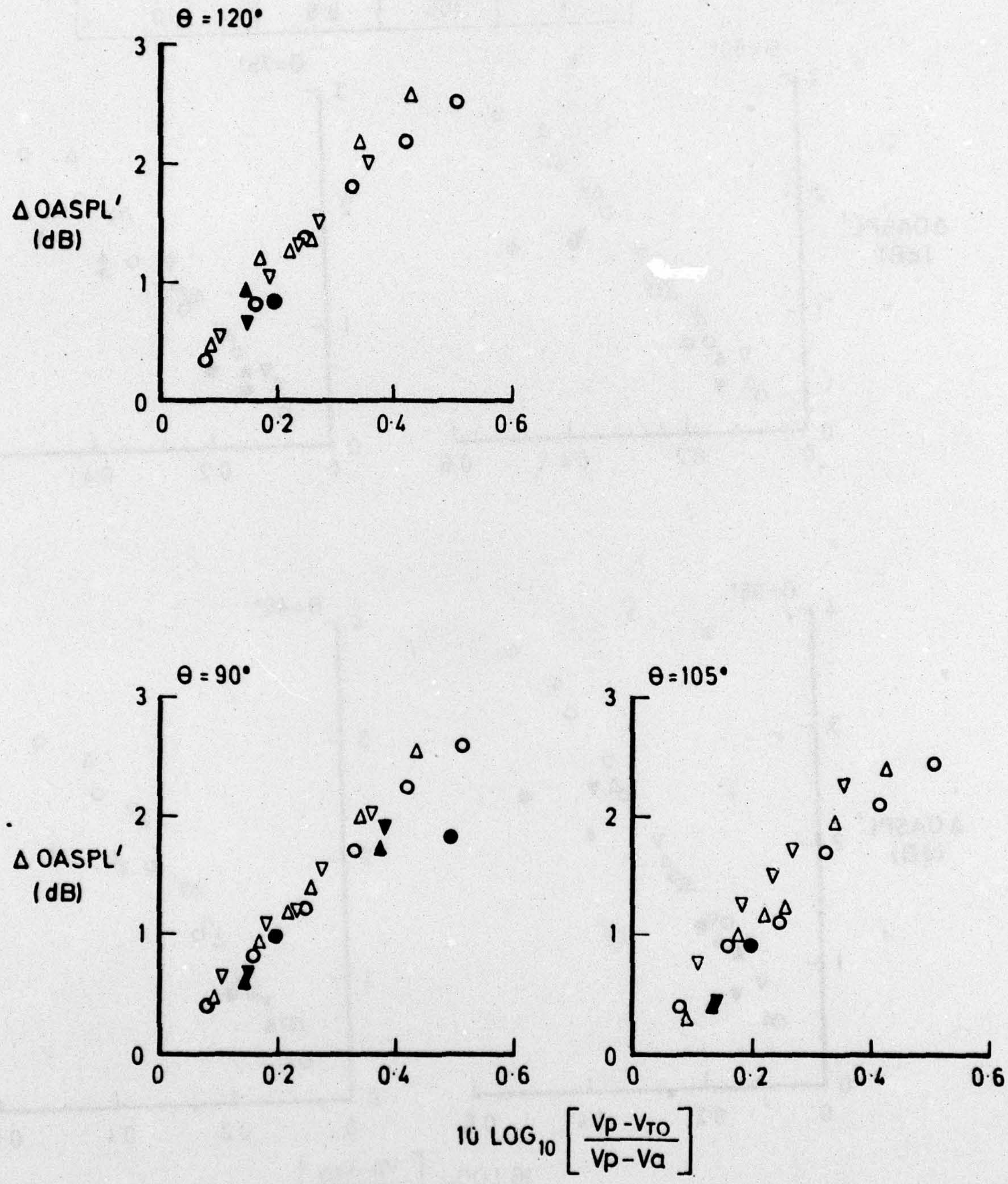


FIG. 18 COAXIAL JET ; UNHEATED PRIMARY, THE EFFECT OF AREA RATIO, θ = 90°, 105°, AND 120°

DETACHABLE ABSTRACT CARDS

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National Gas Turbine Est. Report 343
1976.
Cocking, B. J.

THE EFFECT OF FLIGHT ON THE NOISE OF SUBSONIC JETS

The noise of a single-stream circular jet and a coaxial jet with coplanar nozzles of 2.5 area ratio has been measured under simulated flight conditions in the RAE 24 ft wind-tunnel. The majority of tests were conducted with the single-stream jet and primary section of the coaxial jet at a nominal temperature of 880 K.

The data have been used to quantify the effect of jet temperature and were combined with measurements from an earlier test series to establish a prediction method for the effect of flight on the noise of single-stream subsonic jets. This method is based on jet noise theory modified by experimentally derived constants.

For coaxial jets it is concluded that the noise reductions, which are independent of the secondary stream velocity, are predicted to an acceptable degree by the method suggested for unheated single-stream jets.

The prediction methods are suitable for both OASPLs and spectra.

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Noise (sound)* ; Flight effects on noise; Jet noise prediction; Subsonic jet noise

17. Abstract

The noise of a single-stream circular jet and a coaxial jet with coplanar nozzles of 2.5 area ratio has been measured under simulated flight conditions in the RAE 24 ft wind-tunnel. The majority of tests were conducted with the single-stream jet and primary section of the coaxial jet at a nominal temperature of 880 K.

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